Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

Meta-Analysis of Nitrogen Removal in Riparian Buffers

Paul M. Mayer,* Steven K. Reynolds, Jr., Marshall D. McCutchen, and Timothy J. Canfield

ABSTRACT

Riparian buffers, the vegetated region adjacent to streams and wetlands, are thought to be effective at intercepting and reducing nitrogen loads entering water bodies. Riparian buffer width is thought to be positively related to nitrogen removal effectiveness by influencing nitrogen retention or removal. We surveyed the scientific literature containing data on riparian buffers and nitrogen concentration in streams and groundwater to identify trends between nitrogen removal effectiveness and buffer width, hydrological flow path, and vegetative cover. Nitrogen removal effectiveness varied widely. Wide buffers (>50 m) more consistently removed significant portions of nitrogen entering a riparian zone than narrow buffers (0–25 m). Buffers of various vegetation types were equally effective at removing nitrogen but buffers composed of herbaceous and forest/herbaceous vegetation were more effective when wider. Subsurface removal of nitrogen was efficient, but did not appear to be related to buffer width, while surface removal of nitrogen was partly related to buffer width. The mass of nitrate nitrogen removed per unit length of buffer did not differ by buffer width, flow path, or buffer vegetation type. Our meta-analysis suggests that buffer width is an important consideration in managing nitrogen in watersheds. However, the inconsistent effects of buffer width and vegetation on nitrogen removal suggest that soil type, subsurface hydrology (e.g., soil saturation, groundwater flow paths), and subsurface biogeochemistry (organic carbon supply, nitrate inputs) also are important factors governing nitrogen removal in buffers.

The USEPA considers nitrogen one of the primary stressors in aquatic ecosystems (USEPA, 2002a). Though nitrogen is an important nutrient for all organisms, excess nitrogen is a pollutant that causes eutrophication in surface water and contaminates groundwater (Carpenter et al., 1998). Streams receive chronic nitrogen inputs in various chemical forms such as nitrate (NO_3^-), ammonia (NH_3), and organic N from upland sources such as fertilizers, animal wastes, leaf litter, leaking sewer lines, atmospheric deposition, and highways (Carpenter et al., 1998; Swackhamer et al., 2004). Subsequent eutrophication leads to environmental impacts such as toxic algal blooms, oxygen depletion, fish kills, and loss of biodiversity (Vitousek et al., 1997).

Nitrogen enters aquatic ecosystems in various forms through multiple pathways. For example, nitrous oxides (NO_X) enter by atmospheric deposition, whereas NO_3^- often enters through groundwater and particulate nitrogen in the form of plant litter and other detritus follows terrestrial routes. NO_3^- is of particular concern as an environmental stressor because it is biologically reactive, poses a human health risk (i.e., methemoglobinemia; USEPA, 2002b), and often is found in groundwater (Welch, 1991).

Riparian buffers are thought to be an effective, sustainable means of protecting aquatic ecosystems against anthropogenic inputs of nitrogen (Phillips, 1989; Verhoeven et al., 2006) in which nitrogen species may be transformed by various processes including plant uptake, microbial immobilization, soil storage, and groundwater mixing (Lowrance et al., 1997) and denitrification, a microbially mediated transformation of NO_3^- to N_2, a gas phase of nitrogen (Korom, 1992). Denitrification removes nitrogen from a system, whereas other biological processes such as uptake by plants eventually return nitrogen to the system through senescence and microbial decay.

Establishing riparian buffers often is considered a best management practice (BMP) by state and federal resource agencies for maintaining water quality (NRCS, 2003; Bernhardt et al., 2005b). Buffer effectiveness depends on buffer ability to intercept and attenuate nitrogen traveling along surface or subsurface pathways. The extent to which riparian buffers attenuate nitrogen and subsequently improve water quality is thought to be a function of buffer width in concert with landscape and hydrogeomorphic characteristics (Vidon and Hill, 2004). By some estimates, the width of a buffer accounts for about 80% of that buffer's nitrogen removal effectiveness (Phillips, 1989). Intuitively, larger and wider riparian buffers should transform and remove more nitrogen from the water. Therefore, numerous State and Federal agencies have guidelines recommending buffers of minimum width to protect stream ecosystems from nutrient inputs (Belt et al., 1992; Christensen, 2000; Lee et al., 2004; Mayer et al., 2005). However, the specific mechanisms responsible for removing nitrogen within buffers are not thoroughly understood. Furthermore, existing information about buffer effectiveness is not synthesized in a practical form and may not be widely distributed to resource managers (Hickey and Doran, 2004). Moreover, managers do not typically have the available resources to assess the effectiveness of site-specific buffers. The purpose of this article is to identify trends in the relations between nitrogen removal capacity and buffer width, as well as hydrological flow path and vegetative cover, extracted from peer-reviewed studies containing empirical data on buffer effectiveness. While we do not provide specific recommendations for buffer width, this meta-analysis of current literature is meant to provide a baseline from which management decisions about riparian buffers can be made in the context of nitrogen attenuation.

USEPA, Office of Research and Development, National Risk Management Research Lab., Ground Water and Ecosystems Restoration Div., 919 Kerr Research Dr., Ada, OK 74821. S.K. Reynolds, Jr., current address, Dep. of Biology, Lake Erie College, 391 W. Washington St., Painesville, OH 44077. M.D. McCutchen, current address, Homer L. Dodge Dep. of Physics and Astronomy, Univ. of Oklahoma, 440 W. Brooks St., Norman, OK 73019. Received 24 Oct. 2006. *Corresponding author (mayer.paul@epa.gov).

Published in J. Environ. Qual. 36:1172–1180 (2007).
Reviews and Analyses
doi:10.2134/jeq2006.0462
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

MATERIALS AND METHODS

Riparian buffers are defined as the zone of vegetation adjacent to streams, rivers, or wetlands (i.e., Lee et al., 2004). For this article, riparian buffer, riparian zone, buffer strip, filter strip, and vegetated filter strip are considered synonyms. We employed database search engines (e.g., Cambridge Abstracts, Google Scholar, etc.) and existing bibliographies (e.g., Correll, 2003) to locate riparian buffer zone literature. We used search terms singly or combination including: riparian, buffer, width, filter strip, vegetated filters, nitrogen, etc. We summarized the results and conclusions from peer-reviewed research papers that contained original data quantifying the effects of riparian buffer width on nitrogen attenuation. Papers that did not relate nitrogen removal to buffer width were not included in the results. Data presented in proceedings and other non-peer-reviewed sources were not included in our meta-analysis.

We calculated nitrogen removal effectiveness in two ways. First, as a percentage based on (i) the percent difference in nitrogen concentration between the influent into and effluent out of the riparian buffer, (ii) percent difference in nitrogen concentration between the terminus of the control buffer and that of the test buffer, or (iii) if recalculation were impossible based on available data, the values presented by the authors were used directly (Appendix 1). We did not distinguish among nitrogen forms when calculating effectiveness as a percentage.

Because NO_3^- was the form of nitrogen most often measured among studies, we also calculated buffer effectiveness as the mean mass of nitrate nitrogen removed in riparian zones per unit distance where authors provided information on influent and effluent concentrations.

Removal effectiveness as a percentage was plotted against buffer width. Linear and nonlinear regression models were fitted to the data to reveal patterns of nitrogen removal based on width. All buffers included in studies for which efficiencies could be calculated were included in the meta-analyses as independent data points.

We grouped studies by vegetation cover type (forest, forested wetland, wetland, herbaceous, herbaceous/forest mix) and by hydrologic flow conditions (e.g., surface vs. subsurface), factors that may influence nutrient attenuation in riparian buffer zones. We then plotted effectiveness against buffer width by these groups.

We also grouped studies by buffer width category (0–25, 26–50, and >50 m, respectively). We chose these categories based on current state recommendations for minimum buffer widths which currently range from 15.5 to 24.2 m (Mayer et al., 2005). Therefore our three width categories include buffers that are as wide as current recommendations (0–25 m), those twice as wide (26–50 m), and buffers much wider than recommended (>50 m). We then analyzed effectiveness (percentage nitrogen removal and nitrate removal per unit length) among buffer factor groups (width category, flow path, and vegetation type) using non-parametric tests because the dependent variables were not normally distributed (Shapiro–Wilk test for normality, $P < 0.001$). All analyses and model fitting were performed with Systat 11.0, Sigma Stat 3.1, and SigmaPlot 9.0 software (SSI, 2004).

RESULTS

Buffer Effectiveness

Overall Patterns

We analyzed data from 89 individual riparian buffers from 45 published studies. Nitrogen removal effectiveness varied widely among studies (Appendix 1). Removal effectiveness at one site was calculated as −258% (Appendix 1), due apparently to very low influent (0.12 mg L^{-1}) and effluent (0.43 mg L^{-1}) nitrate concentrations, and was removed from further analysis as an outlier. The remaining data showed that overall, buffers were effective at removing large proportions of the nitrogen from water flowing through riparian zones (mean % ± 1 standard error [SE]: 67.5 ± 4.0, $N = 88$; Table 1).

A small but significant proportion of the variance in removal of nitrogen was explained by buffer width ($R^2 = 0.09$, $P = 0.005$, $N = 88$; Fig. 1, Table 1). That is, wider buffers tended to remove more nitrogen, but other factors must also have affected effectiveness. Overall, exponential models ($y = ax^b$) were the simplest models that best fit the effectiveness to buffer relationships. Accordingly, 50, 75, and 90% removal efficiencies were estimated to occur among all buffers approximately 4, 49, and 149 m wide, respectively (Fig. 1, Table 1). These estimates had large variances based on SE of the regression models (Table 1).

Table 1. Percent effectiveness of riparian buffers at removing nitrogen. Buffer widths necessary to achieve a given percent effectiveness (50, 75, 90%) are approximate values predicted by the nonlinear model, $y = ax^b$. Effectiveness was not predicted (np) for models with R^2 Values ≤ 0.2 except for "all studies" model.

Buffer variable	N	Mean removal effectiveness	Regression model	R^2	SE†	P	Approximate buffer width by predicted effectiveness 50%	75%	90%
		% ± 1 SE					m		
All studies	88	67.5 ± 4.0	$y = 39.5x^{0.1644}$	0.09	36.2	0.005	4	49	149
Width category									
0–25 m	45	57.9 ± 6.0	$y = 42.1x^{0.1337}$	0.01	40.7	0.5	np	np	np
26–50 m	24	71.4 ± 7.8	$y = 50.6x^{0.0964}$	0.00	39.0	0.8	np	np	np
>50 m	19	85.2 ± 4.8	$y = 56.9x^{0.0883}$	0.03	21.0	0.5	np	np	np
Flow path									
Surface	23	41.6 ± 7.1	$y = 14.6x^{0.3722}$	0.21	30.9	0.03	27	81	131
Subsurface	65	76.7 ± 4.3	$y = 62.0x^{0.0631}$	0.02	34.7	0.3	np	np	np
Vegetation type									
Forest	31	72.2 ± 6.9	$y = 45.7x^{0.1225}$	0.04	38.4	0.3	np	np	np
Forested wetland	7	85.0 ± 5.2	$y = 85.0x^{0.0809}$	0.00	15.1	1.0	np	np	np
Herbaceous	32	54.0 ± 7.5	$y = 18.0x^{0.3631}$	0.21	38.5	0.009	17	51	84
Herbaceous/forest	11	79.5 ± 7.3	$y = 41.5x^{0.2044}$	0.39	20.1	0.04	3	18	44
Wetland	7	72.3 ± 11.9	$y = 67.8x^{0.0244}$	0.01	34.2	0.9	np	np	np

† SE represents the standard error of the regression estimate.

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

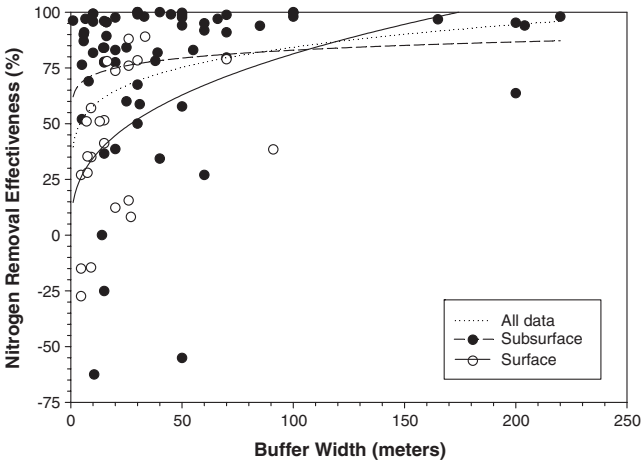

Fig. 1. Relationships of nitrogen removal effectiveness to riparian buffer width over all studies and analyzed by water flow path. Lines are fitted to model $y = ax^b$.

Buffer Width Category

Effectiveness was not related to buffer width when analyzing buffers within width categories ($P > 0.5$, Table 1), suggesting that any effect of buffer width on nitrogen removal occurs only after buffer size reaches a width threshold. This suggestion is supported by the observation that effectiveness differed among buffer width categories (Kruskal–Wallis $H = 10.3$, df = 2, $P = 0.006$; Fig. 2, Table 1). Nitrogen removal effectiveness of buffers >50 m wide was greater than that of buffers 0 to 25 m, whereas effectiveness of buffers 26 to 50 m did not differ from the other categories (Dunn's method of multiple comparisons $Q = 3.0$, $P < 0.05$; Fig. 2, Table 1). Thus, wider buffers are likely to be more efficient zones of nitrogen removal than narrower buffers.

Surface versus Subsurface Flow

Nitrogen removal effectiveness also differed by flow pattern. Subsurface removal of nitrogen was much more efficient than surface removal (Mann–Whitney $U = 1247.5$, df = 1, $P < 0.001$; Fig. 3, Table 1). Furthermore, subsurface removal of nitrogen did not appear to be related to buffer width ($R^2 = 0.02$, $P = 0.3$; Fig. 1, Table 1), whereas a small but significant proportion of the variance in surface removal of nitrogen was explained by buffer width ($R^2 = 0.21$, $P = 0.03$; Fig. 1, Table 1). That is, wider buffers removed more nitrogen in surface runoff. While some narrow buffers (<15 m) removed significant proportions of nitrogen, six studies (three surface and three subsurface flow) found that narrow buffers actually contributed nitrogen to riparian zones (i.e., had negative effectiveness values; Appendix 1; Fig. 1). Such cases are likely to be short-term events due to nitrification or high rainfall events that lead to rapid inputs of nitrogen (Dillaha et al., 1988; Magette et al., 1989; Sabater et al., 2003). Based on the model $y = ax^b$, 50, 75, and 90% nitrogen removal efficiencies in surface flow were estimated to occur in buffers approximately 27, 81, and 131 m wide, respectively (Fig. 1, Table 1). These models also had large associated variances (SE; Table 1).

Vegetation Type

Overall nitrogen removal effectiveness did not vary by buffer vegetation type (Kruskal–Wallis $H = 6.9$, df = 4, $P = 0.14$; Fig. 4 and Table 1) suggesting that all buffers were equally effective at removing nitrogen. Forested, forested/wetland, and wetland buffers showed no relationship between buffer width and nitrogen removal effectiveness; however, effectiveness of herbaceous and herbaceous/forested buffers increased with width (Fig. 5, Table 1). Based on the model $y = ax^b$, nitrogen removal efficiencies of 50, 75, and 90% were estimated for herbaceous buffers approximately 17, 51, and 84 m wide and for herbaceous/forest buffers approximately 3, 18, and 44 m wide, respectively (Table 1). Models had large variances (SE; Table 1). Four herbaceous and two forested buffers added to nitrogen loads where buffers were <15 m (Fig. 5). In such cases, nitrification or high

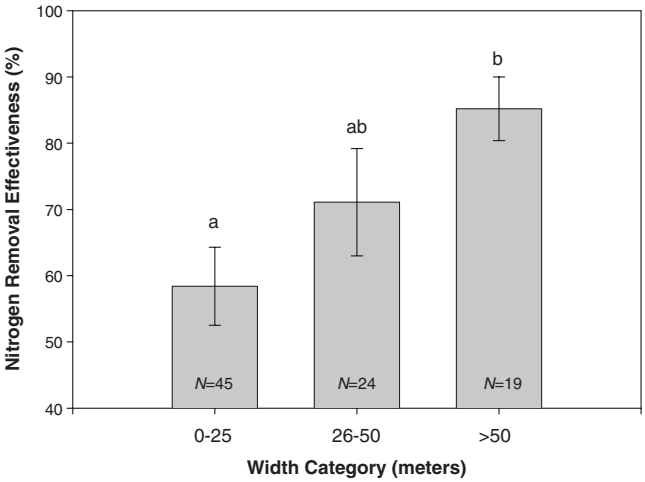

Fig. 2. Nitrogen removal effectiveness in riparian buffers by buffer width category. Bars represent means ± 1 standard error. Mean ranks of width categories differ if denoted by different letters (Kruskal–Wallis one-way analysis of variance on ranks with Dunn's method of multiple comparisons, $P < 0.05$).

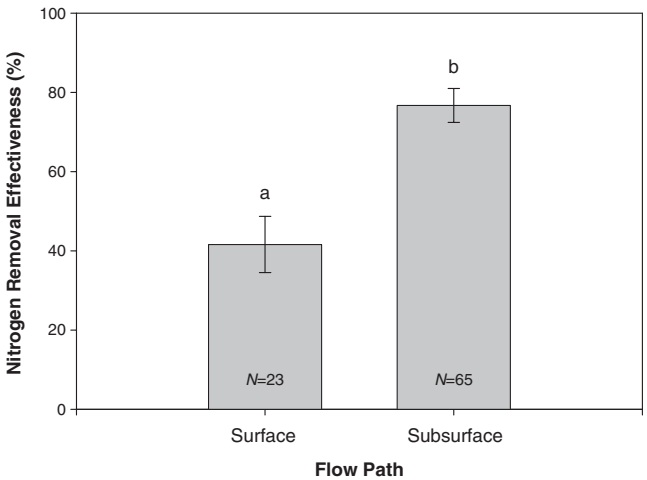

Fig. 3. Nitrogen removal effectiveness in riparian buffers by water flow path. Bars represent means ± 1 standard error. Mean ranks of flow paths differ if denoted by different letters (Mann–Whitney U test on ranks, $P < 0.001$).

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

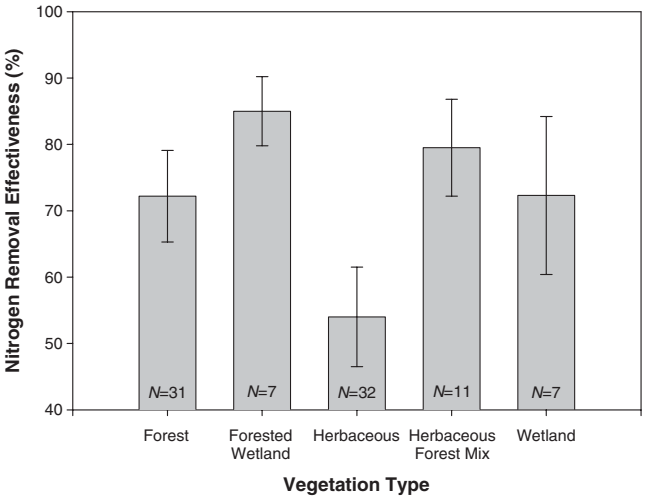

Fig. 4. Nitrogen removal effectiveness in riparian buffers by buffer vegetation type. Bars represent means ± 1 standard error. Mean ranks of vegetation types do not differ (Kruskal–Wallis one-way analysis of variance on ranks, $P = 0.14$).

rainfall events may lead to short-term and/or rapid inputs of nitrogen (Sabater et al., 2003).

Mass Removal of Nitrate Nitrogen

We analyzed data from 60 riparian buffers for which influent and effluent nitrate nitrogen concentrations were available. Similar to percent removal effectiveness, mass removal of nitrate nitrogen per unit length varied widely among studies. Overall, buffers removed nitrate nitrogen at a rate of (mean ± 1 SE) 0.394 ± 0.084 mg L^{-1} m^{-1}. Unlike effectiveness, nitrate nitrogen removal did not differ among width categories (Kruskal–Wallis $H = 4.8$, df = 2, $P = 0.09$; Table 2), suggesting that nitrate removal rate remained constant across the entire length of buffers.

Nitrate removal was not related to flow pattern (Mann–Whitney $U = 256.0$, df = 1, $P = 0.11$; Table 2). Nitrate removal also was not related to buffer vegetation type (Kruskal–Wallis, df = 4, $H = 7.3$, $P = 0.12$; Fig. 6, Table 2).

Table 2. Mass removal of nitrate nitrogen in riparian buffers.

Buffer variable	N	Mean mass of NO_3^- removed per unit length	1 SE†
		mg L^{-1} m^{-1}	
All studies	60	0.394	0.084
Width category			
0–25 m	25	0.463	0.106
26–50 m	19	0.377	0.127
>50 m	16	0.305	0.227
Flow path			
Surface flow	7	0.339	0.299
Subsurface flow	53	0.401	0.087
Vegetative cover			
Forest	26	0.186	0.065
Forested wetland	3	0.617	0.333
Herbaceous	19	0.497	0.199
Herbaceous/forest	6	0.293	0.138
Wetland	6	0.957	0.359

† 1 SE represents 1 standard error of the means.

DISCUSSION

Our meta-analysis suggests that wider buffers tend to be more effective at removing nitrogen. Low R^2 values of the overall regression analysis suggest that factors other than buffer width influence buffer effectiveness such as (i) vegetation and depth of the root zone where plants can take up nitrogen (Asmussen et al., 1979; Cooper, 1990), and (ii) hydrological flow paths that favor microbial denitrification (i.e., saturated anaerobic soils, adequate carbon supplies, floodplain connections; Dillaha et al., 1989; Simmons et al., 1992; Hanson et al., 1994; Speiran et al., 1998; Leeds-Harrison et al., 1999; Sloan et al., 1999; Hill et al., 2000, 2004; Steinhart et al., 2001; Schade et al., 2001, 2002; Groffman et al., 2003, 2005; Sabater et al., 2003; Richardson et al., 2004). Furthermore, buffer width was not a factor affecting nitrogen removal effectiveness within buffer width categories, indicating that trends in effectiveness are evident only across a broader range of buffer size. Yet, mean

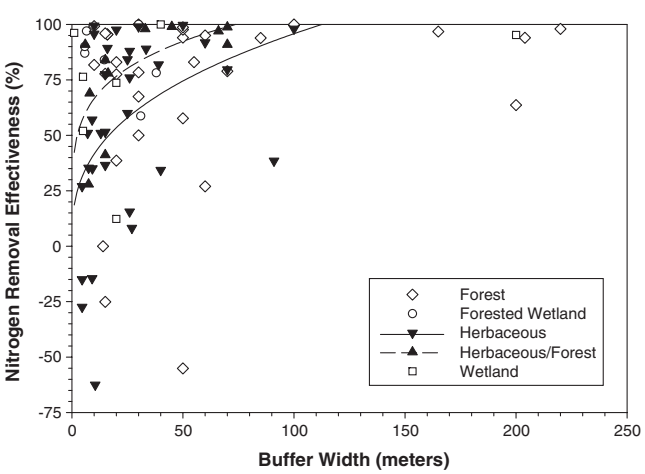

Fig. 5. Relationships of nitrogen removal effectiveness to riparian buffer width analyzed by vegetation type. Lines are fitted to model $y = ax^b$. Only the regression lines for herbaceous and herbaceous/forest vegetation types are shown because model results for other vegetation types were not significant ($P > 0.3$).

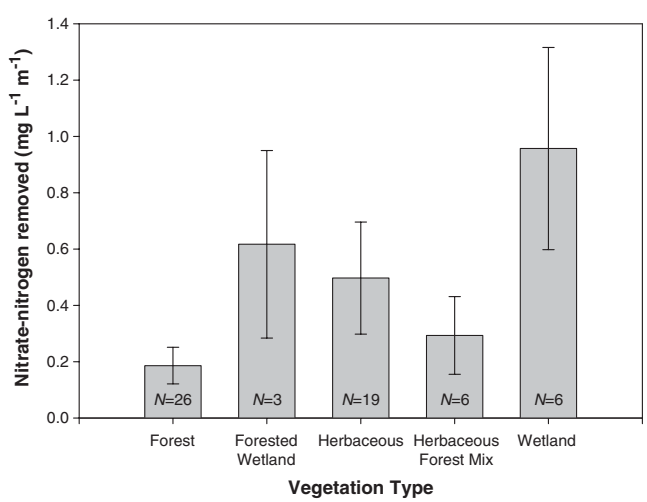

Fig. 6. Mass of nitrate nitrogen removed in riparian buffers by buffer vegetation type. Bars represent means ± 1 standard error. Mean ranks of vegetation types do not differ (Kruskal–Wallis one-way analysis of variance on ranks, $P = 0.12$).

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

nitrogen removal effectiveness in buffers >50 m wide was significantly higher than in narrow buffers (0–25 m), suggesting that buffer width is an important consideration for nitrogen management in watersheds.

Overall, suburface nitrogen removal is more efficient than removal through surface flow. Furthermore, subsurface nitrogen removal may be more directly influenced by soil type, watershed hydrology (e.g., soil saturation, groundwater flow paths, etc.), and subsurface biogeochemistry (organic carbon supply, high NO_3^- inputs) through cumulative effects on microbial denitrification activity than on buffer width per se. Surface flows bypass zones of denitrification, and thus effectively remove nitrogen only when buffers are wide enough and have adequate vegetation cover to control erosion and filter movement of particulate forms of nitrogen. Herbaceous buffers, for example, may be better at intercepting particulate nitrogen in the sediments of surface runoff by reducing channelized flow. Based on a limited data set fitted to a log-linear model, Oberts and Plevan (2001) found that NO_3^- retention in wetland buffers was positively related to buffer width (R^2 values ranged from 0.35–0.45). Nitrogen removal efficiencies of 65 to 75% and 80 to 90% were predicted for wetland buffers 15 and 30 m wide, respectively, depending on whether NO_3^- was measured in surface or subsurface flow (Oberts and Plevan, 2001).

Our meta-analysis suggests that vegetation type has a limited impact on buffer effectiveness (Table 1). Only buffers with herbaceous vegetation were more effective when wider (Table 1). However, buffer width may indirectly affect factors promoting denitrification. For example, narrow buffers that produce little vegetative biomass may not provide sufficient stocks of organic material for microbial denitrifiers.

Regardless of width, buffer integrity should be protected against (i) soil compaction (e.g., vehicles, livestock, and construction of impervious surfaces) that might inhibit infiltration or disrupt water flow patterns (Dillaha et al., 1989; NRC, 2002), (ii) excessive leaf litter removal or alteration of the natural plant community (e.g., raking, tree thinning, introduction of invasive species) that might reduce carbon-rich organic matter from reaching the stream, and (iii) practices that might disconnect the stream channel from the flood plain (i.e., urbanization, channelization, bank erosion, stream incision, hard drainage surfaces, and drain tiles) and thereby reduce the spatial and temporal extent of soil saturation (Paul and Meyer, 2001; Groffman et al., 2003, 2005).

CONCLUSIONS

Based on our meta-analysis, riparian buffers of various types are effective at reducing nitrogen in riparian zones, especially nitrogen flowing in the subsurface. Our study shows that, while some narrow buffers (0–25 m) remove nitrogen, wider buffers (>50 m) more consistently removed significant portions of nitrogen probably by providing more area for root uptake of nitrogen (Asmussen et al., 1979; Cooper, 1990) or more sites where groundwater conditions favor denitrification (Hanson et al., 1994; Leeds-Harrison et al., 1999; Sloan et al., 1999; Hill et al., 2000, 2004; Schade et al., 2001, 2002; Steinhart et al., 2001; Sabater et al., 2003; Richardson et al., 2004). Maintaining buffers around stream headwaters (Peterson et al., 2001; Richardson et al., 2004; Bernhardt et al., 2005a; Bernot and Dodds, 2005) will likely be most effective at maintaining overall watershed water quality while restoring degraded riparian zones, and stream channels may improve nitrogen removal capacity (Groffman et al., 2005). However, because streams and riparian zones have limited capacity to process nitrogen, watershed nutrient management efforts also must include control and reduction of point and nonpoint sources of nitrogen from atmospheric, terrestrial, and aquatic inputs. Furthermore, overtaxing the nutrient removal capacity of riparian zones and floodplain wetlands may lead to losses of biodiversity and production of nitrous oxides (Verhoeven et al., 2006). Establishing a network of buffers adequate to maintain watershed water quality will be dependent on local and centralized conservation activities as well as government regulations and standards (Mayer et al., 2005; Verhoeven et al., 2006).

ACKNOWLEDGMENTS

We are grateful to S. Sabater for providing original data associated with Sabater et al. (2003). T. Wiggins assisted in the search for literature. This manuscript benefited from comments by D. Niyogi, D. Walters, S. Wenger, and three anonymous reviewers. The USEPA through its Office of Research and Development funded and managed the research described here through in-house efforts. This manuscript has not been subject to EPA review; therefore it does not necessarily reflect the views of the EPA and no official endorsement should be inferred.

REFERENCES

Asmussen, L.E., J.M. Sheridan, and C.V. Booram, Jr. 1979. Nutrient movement in stream flow from agricultural watersheds in the Georgia Coastal Plain. Trans. ASAE 22:809–815, 821.

Belt, G.H., J. O'Laughlin, and T. Merrill. 1992. Design of forest riparian buffer strips for the protection of water quality: Analysis of scientific literature. Report No. 8. Idaho Forest, Wildlife, and Range Policy Group, Univ. of Idaho, Moscow, Idaho.

Bernhardt, E.S., G.E. Likens, R.O. Hall, Jr., D.C. Buso, S.G. Fisher, T.M. Burton, J.L. Meyer, W.H. McDowell, M.S. Mayer, W.B. Bowden, S.E.G. Findlay, K.H. MacNeale, R.S. Stelzer, and W.H. Lowe. 2005a. Can't see the forest for the stream? In-stream processing and terrestrial nitrogen exports. Bioscience 55:219–230.

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005b. Synthesizing U.S. river restoration efforts. Science 308:636–637.

Bernot, M.J., and W.K. Dodds. 2005. Nitrogen retention, removal, and saturation in lotic ecosystems. Ecosystems 8:442–453.

Bingham, S.C., P.W. Westerman, and M.R. Overcash. 1980. Effect of grass buffer zone length in reducing the pollution from land application areas. Trans. ASAE 23:330–335.

Borin, M., and E. Bigon. 2002. Abatement of NO_3–N concentration in agricultural waters by narrow buffer strips. Environ. Pollut. 117: 165–168.

Brüsch, W., and B. Nilsson. 1993. Nitrate transformation and water movement in a wetland area. Hydrobiologia 251:103–111.

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

Burns, D.A., and L. Nguyen. 2002. Nitrate movement and removal along a shallow groundwater flow path in a riparian wetland within a sheep-grazed pastoral catchment: Results of a tracer study. N. Z. J. Mar. Freshwater Res. 36:371–385.

Carpenter, S., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Issues in Ecology 3:1–12.

Cey, E.E., D.L. Rudolph, R. Aravena, and G. Parkin. 1999. Role of the riparian zone in controlling the distribution and fate of agricultural nitrogen near a small stream in southern Ontario. J. Contam. Hydrol. 37:45–67.

Christensen, D. 2000. Protection of riparian ecosystems: A review of the best available science. Tech. Rep. Jefferson County Natural Resources Div., Port Townsend, WA.

Clausen, J.C., K. Guillard, C.M. Sigmund, and K.M. Dors. 2000. Water quality changes from riparian buffer restoration in Connecticut. J. Environ. Qual. 29:1751–1761.

Cooper, A.B. 1990. Nitrate depletion in the riparian zone and stream channel of a small headwater catchment. Hydrobiologia 202:13–26.

Correll, D. 2003. Vegetated stream riparian zones: Their effects on stream nutrients, sediments, and toxic substances. 13th ed. Sustainable Florida Ecosystems, Inc., Crystal River, FL.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Trans. ASAE 32:513–519.

Dillaha, T.A., J.H. Sherrard, D. Lee, S. Mostaghimi, and V.O. Shanholtz. 1988. Evaluation of vegetative filter strips as a best management practice for feed lots. J. Water Pollut. Control Fed. 60:1231–1238.

Dukes, M.D., R.O. Evans, J.W. Gilliam, and S.H. Kunickis. 2002. Effect of riparian buffer width and vegetation on shallow groundwater quality in the middle coastal plain of North Carolina. Trans. ASAE 45:327–336.

Fustec, E., A. Mariotti, X. Grillo, and J. Sajus. 1991. Nitrate removal by denitrification in alluvial ground water: Role of a former channel. J. Hydrol. 123:337–354.

Groffman, P.M., D.J. Bain, L.E. Band, K.T. Belt, G.S. Brush, J.M. Grove, R.V. Pouyat, I.C. Yesilonis, and W.C. Zipperer. 2003. Down by the riverside: Urban riparian ecology. Front. Ecol. Environ. 6:315–321.

Groffman, P.M., G. Howard, A.J. Gold, and W.M. Nelson. 1996. Microbial nitrate processing in shallow groundwater in a riparian forest. J. Environ. Qual. 25:1309–1316.

Groffman, P.M., A.M. Dorsey, and P.M. Mayer. 2005. N processing within geomorphic structures in urban streams. J. N. Am. Benthol. Soc. 24:613–625.

Hanson, G.C., P.M. Groffman, and A.J. Gold. 1994. Symptoms of nitrogen saturation in a riparian wetland. Ecol. Appl. 4:750–756.

Haycock, N.E., and T.P. Burt. 1993. Role of floodplain sediments in reducing the nitrate concentration of subsurface run-off: A case study in the Cotswolds, UK. Hydrol. Processes 7:287–295.

Haycock, N.E., and G. Pinay. 1993. Groundwater nitrate dynamics in grass and poplar vegetated riparian buffer strips during the winter. J. Environ. Qual. 22:273–278.

Hefting, M.M., R. Bobbink, and H. de Caluwe. 2003. Nitrous oxide emission and denitrification in chronically nitrate-loaded riparian buffer zones. J. Environ. Qual. 32:1194–1203.

Hefting, M.M., and J.J.M. de Klein. 1998. Nitrogen removal in buffer strips along a lowland stream in the Netherlands: A pilot study. Environ. Pollut. 102(S1):521–526.

Hickey, M.B.C., and B. Doran. 2004. A review of the efficiency of buffer strips for the maintenance and enhancement of riparian ecosystems. Water Qual. Res. J. Can. 39:311–317.

Hill, A.R., K.J. Devito, S. Campagnolo, and K. Sanmugadas. 2000. Subsurface denitrification in a forest riparian zone: Interactions between hydrology and supplies of nitrate and organic carbon. Biogeochemistry 51:193–223.

Hill, A.R., P.G.F. Vidon, and J. Langat. 2004. Denitrification potential in relation to lithology in five headwater riparian zones. J. Environ. Qual. 33:911–919.

Hubbard, R.K., and R. Lowrance. 1997. Assessment of forest management effects on nitrate removal by riparian buffer systems. Trans. ASAE 40:383–391.

Hubbard, R.K., and J.M. Sheridan. 1989. Nitrate movement to groundwater in the southeastern Coastal Plain. J. Soil Water Conserv. 44:20–27.

Jacobs, T.C., and J.W. Gilliam. 1985. Riparian losses of nitrate from agricultural drainage waters. J. Environ. Qual. 14:472–478.

Jordan, T.E., D.L. Correll, and D.E. Weller. 1993. Nutrient interception by a riparian forest receiving inputs from adjacent cropland. J. Environ. Qual. 22:467–473.

Korom, S.F. 1992. Natural denitrification in the saturated zone: A review. Water Resour. Res. 28:1657–1668.

Lee, K.-H., T.M. Isenhart, and R.C. Schultz. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. J. Soil Water Conserv. 58:1–7.

Lee, P., C. Smyth, and S. Boutin. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. Environ. Manage. 70:165–180.

Leeds-Harrison, P.B., J.N. Quinton, M.J. Walker, C.L. Sanders, and T. Harrod. 1999. Grassed buffer strips for the control of nitrate leaching to surface waters in headwater catchments. Ecol. Eng. 12: 299–313.

Lowrance, R. 1992. Groundwater nitrate and denitrification in a coastal plain riparian forest. J. Environ. Qual. 21:401–405.

Lowrance, R., L.S. Altier, J.D. Newbold, R.R. Schnabel, P.M. Groffman, J.M. Denver, D.L. Correll, J.W. Gilliam, J.L. Robinson, R.B. Brinsfield, K.W. Staver, W. Lucas, and A.H. Todd. 1997. Water quality functions of riparian forest buffer systems in Chesapeake Bay Watersheds. Environ. Manage. 21:687–712.

Lowrance, R.R., R.L. Todd, and L.E. Asmussen. 1984. Nutrient cycling in an agricultural watershed: I. Phreatic movement. J. Environ. Qual. 13:22–27.

Lynch, J., E. Corbett, and K. Mussallem. 1985. Best management practices for controlling nonpoint source pollution of forested watersheds. J. Soil Water Conserv. 1:164–167.

Magette, W.L., R.B. Brinsfield, R.E. Palmer, and J.D. Wood. 1989. Nutrient and sediment removal by vegetated filter strips. Trans. ASAE 32:663–667.

Martin, T.L., N.K. Kaushik, H.R. Whiteley, S. Cook, and J.W. Nduhiu. 1999. Groundwater nitrate concentrations in the riparian zones of two southern Ontario streams. Can. Water Resour. J. 24:125–138.

Mayer, P.M., S.K. Reynolds, M.D. McMutchen, and T.J. Canfield. 2005. Riparian buffer width, vegetative cover, and nitrogen removal effectiveness: A review of current science and regulations, EPA/600/R-05/118. USEPA, Office of Research and Development, Washington, DC.

National Research Council. 2002. Riparian areas: Functions and strategies for management. National Academy Press, Washington, DC.

Natural Resources Conservation Service. 2003. National handbook of conservation practices. USDA, Washington, DC.

Oberts, G., and A. Plevan. 2001. Benefits of wetland buffers: A study of functions, values, and size. Tech. Rep. Emmons and Oliver Resources, Inc., Oakdale, MN.

Osborne, L.L., and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biol. 29:243–258.

Paul, M.J., and J.L. Meyer. 2001. Streams in the urban landscape. Annu. Rev. Ecol. Syst. 32:333–365.

Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology 65:1466–1475.

Peterson, B.J., W.M. Wollheim, P.J. Mulholland, J.R. Webster, J.L. Meyer, J.L. Tank, E. Marti, W.B. Bowden, H.M. Valett, A.E. Hershey, W.H. McDowell, W.K. Dodds, S.K. Hamilton, S. Gregory, and D.D. Morrall. 2001. Control of nitrogen export from watersheds by headwater streams. Science 292:86–90.

Phillips, J.D. 1989. An evaluation of the factors determining the effectiveness of water quality buffer zones. J. Hydrol. 107:133–145.

Pinay, G., and H. Decamps. 1988. The role of riparian woods in regulating nitrogen fluxes between alluvial aquifer and surface water: A conceptual model. Regulated Rivers 2:507–516.

Pinay, G., L. Roques, and A. Fabre. 1993. Spatial and temporal patterns of denitrification in riparian forest. J. Appl. Ecol. 30:581–591.

Prach, K., and O. Rauch. 1992. On filter effects of ecotones. Ekol. CSFR 11:293–298.

Puckett, L.J., T.K. Cowdery, P.B. McMahon, L.H. Tornes, and J.D. Stoner. 2002. Using chemical, hydrologic, and age dating analysis to delineate redox processes and flow paths in the riparian zone of a glacial outwash aquifer-stream system. Water Resour. Res. 38:10.1029.

Richardson, W.B., E.A. Strauss, L.A. Bartsch, E.M. Monroe, J.C. Cavanaugh, L. Vingum, and D.M. Soballe. 2004. Denitrification in the Upper Mississippi River: Rates, controls, and contribution to nitrate flux. Can. J. Fish. Aquat. Sci. 61:1102–1112.

Sabater, S., A. Butturini, J.C. Clement, T. Burt, D. Dowrick, M. Hefting, V. Matre, G. Pinay, C. Postolache, M. Rzepecki, and F. Sabater. 2003. Nitrogen removal by riparian buffers along a European climatic gradient: Patterns and factors of variation. Ecosystems 6:20–30.

Schade, J.D., S.G. Fisher, N.B. Grimm, and J.A. Seddon. 2001. The influence of a riparian shrub on nitrogen cycling in a Sonoran Desert stream. Ecology 82:3363–3376.

Schade, J.D., E. Marti, J.R. Welter, S.G. Fisher, and N.B. Grimm. 2002. Sources of nitrogen to the riparian zone of a desert stream: Implications for riparian vegetation and nitrogen retention. Ecosystems 5:68–79.

Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. 1999. Filter strip performance and processes for different vegetation, widths, and contaminants. J. Environ. Qual. 28:1479–1489.

Schoonover, J.E., and K.W.J. Williard. 2003. Ground water nitrate reduction in giant cane and forest riparian buffer zones. J. Am. Water Resour. Assoc. 39:347–354.

Schultz, R.C., J.P. Colletti, T.M. Isenhart, W.W. Simpkings, C.W. Mize, and M.L. Thompson. 1995. Design and placement of a multispecies riparian buffer strip. Agrofor. Syst. 29:201–225.

Schwer, C.B., and J.C. Clausen. 1989. Vegetative filter strips of dairy milkhouse wastewater. J. Environ. Qual. 18:446–451.

Simmons, R.C., A.J. Gold, and P.M. Groffman. 1992. Nitrate dynamics in riparian forests: Groundwater studies. J. Environ. Qual. 21:659–665.

Sloan, A.J., J.W. Gillian, J.E. Parsons, R.L. Mikkelsen, and R.C. Riley. 1999. Groundwater nitrate depletion in a swine lagoon effluent-irrigated pasture and adjacent riparian zone. J. Soil Water Conserv. 54:651–656.

Speiran, G.K., P.A. Hamilton, and M.D. Woodside. 1998. Natural processes for managing nitrate in groundwater discharged to Chesapeake Bay and other surface waters: More than forest buffers. USGS Fact Sheet FS-178-97. USGS, Washington, DC.

Spruill, T.B. 2000. Statistical evaluation of effects of riparian buffers on nitrate and groundwater quality. J. Environ. Qual. 29:1523–1538.

Spruill, T.B. 2004. Effectiveness of riparian buffers in controlling groundwater discharge of nitrate to streams in selected hydrogeological settings of the North Carolina Coastal Plain. Water Sci. Technol. 49:63–70.

SSI. 2004. Systat Software Inc. Richmond, CA.

Steinhart, G.S., G.E. Likens, and P.M. Groffman. 2001. Denitrification in stream sediments in five northeastern (USA) streams. Verh. Int. Ver. Theor. Angew. Limnol. 27:1331–1336.

Swackhamer, D.L., H.W. Paerl, S.J. Eisenreich, J. Hurley, K.C. Hornbuckle, M. McLachlan, D. Mount, D. Muir, and D. Schindler. 2004. Impacts of atmospheric pollutants on aquatic ecosystems. Issues in Ecology 12:1–24.

USEPA. 2002a. National water quality inventory: 2000 Rep., EPA/841/R-02/001. Office of Water, Washington, DC.

USEPA. 2002b. National primary drinking water standards, EPA/816/F-02/013. Office of Water, Washington, DC.

Vellidis, G., R. Lowrance, P. Gay, and R.K. Hubbard. 2003. Nutrient transport in a restored riparian wetland. J. Environ. Qual. 32:711–726.

Verhoeven, J.T.A., B. Arheimer, C. Yin, and M.M. Hefting. 2006. Regional and global concerns over wetlands and water quality. Trends Ecol. Evol. 21:96–103.

Vidon, P.G.F., and A.R. Hill. 2004. Landscape controls on nitrate removal in stream riparian zones. Water Resour. Res. 40:W03201.

Vitousek, P.M., J. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and G.D. Tilman. 1997. Human alteration of the global nitrogen cycle: Causes and consequences. Issues in Ecology 1:1–15.

Welch, D.J. 1991. Riparian forest buffers–Functional and design protection and enhancement of water resources. Tech. Rep. NA-PR-07-91. USDA Forest Service, Radnor, Pennsylvania.

Young, R.A., T. Huntrods, and W. Anderson. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. J. Environ. Qual. 9:483–487.

Zirschky, J., D. Crawford, L. Norton, S. Richards, and D. Deemer. 1989. Ammonia removal using overland flow. J. Water Pollut. Control Fed. 61:1225–1232.

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.

Appendix 1. Summary table of riparian buffer effectiveness at removing nitrogen (N) by vegetation type, hydrologic flow path, buffer width, and soil type.

Vegetation type	Flow path	Buffer width	N form	NO_3^- Concentration Mean influent	NO_3^- Concentration Mean effluent	Nitrogen removal effectiveness	NO_3^- removed	Study
		m		mg L^{-1}	mg L^{-1}	%	mg L^{-1} m^{-1}	
Herbaceous	surface	4.6	Total N	–	–	−15	–	Magette et al. (1989)
Herbaceous	surface	9.2	Total N	–	–	35	–	Magette et al. (1989)
Herbaceous	surface	7.5	Total N	68	44	35	–	Schmitt et al. (1999)
Herbaceous	surface	15	Total N	68	33	51	–	Schmitt et al. (1999)
Herbaceous	surface	4.6	NO_3^-	1.86	2.37	−27	−0.11	Dillaha et al. (1988)
Herbaceous	surface	9.1	NO_3^-	1.86	2.13	−15	−0.03	Dillaha et al. (1988)
Herbaceous	surface	4.6	NO_3^-	–	–	27	–	Dillaha et al. (1989)
Herbaceous	surface	9.1	NO_3^-	–	–	57	–	Dillaha et al. (1989)
Herbaceous	surface	91	Total N	21.6	13.3	38	–	Zirschky et al. (1989)
Herbaceous	surface	27	NO_3^-	0.37	0.34	8	<0.01	Young et al. (1980)
Herbaceous	surface	26	NH_3	3.61	3.05	16	–	Schwer and Clausen (1989)
Herbaceous	surface	26	TKN	48.9	11.76	76	–	Schwer and Clausen (1989)
Herbaceous	surface	7.1	NO_3^-	–	–	51	–	Lee et al. (2003)
Herbaceous	surface	13	NO_3^-	–	–	51	–	Bingham et al. (1980)
Herbaceous	surface	33.4	NO_3^-	–	–	89	–	Bingham et al. (1980)
Herbaceous	surface	26	NO_3^-	–	–	88	–	Bingham et al. (1980)
Herbaceous	subsurface	40	NO_3^-	0.35	0.23	34	<0.01	Sabater et al. (2003)
Herbaceous	subsurface	60	NO_3^-	1.7	0.14	92	0.03	Sabater et al. (2003)
Herbaceous	subsurface	20	NO_3^-	12.42	0.30	98	0.61	Sabater et al. (2003)
Herbaceous	subsurface	10.5	NO_3^-	0.08	0.13	−63	−0.01	Sabater et al. (2003)
Herbaceous	subsurface	15	NO_3^-	11.56	7.34	37	0.28	Sabater et al. (2003)
Herbaceous	subsurface	15	NO_3^-	12.35	2.79	77	0.64	Sabater et al. (2003)
Herbaceous	subsurface	25	NO_3^-	15.5	6.2	60	0.37	Vidon and Hill (2004)
Herbaceous	subsurface	70	NO_3^-	1.55	0.32	80	0.02	Martin et al. (1999)
Herbaceous	subsurface	39	NO_3^-	16.5	3	82	0.35	Osborne and Kovacic (1993)
Herbaceous	subsurface	25	NO_3^-	12.15	1.92	84	0.41	Hefting and de Klein (1998)
Herbaceous	subsurface	16	NO_3^-	2.8	0.3	89	0.16	Haycock and Burt (1993)
Herbaceous	subsurface	10	NO_3^-	7	0.3	96	0.67	Hefting et al. (2003)
Herbaceous	subsurface	100	NO_3^-	375	< 5	98	3.70	Prach and Rauch (1992)
Herbaceous	subsurface	10	NO_3^-	7.54	0.05	99	0.75	Schoonover and Williard (2003)
Herbaceous	subsurface	30	NO_3^-	44.7	0.45	99	1.48	Vidon and Hill (2004)
Herbaceous	subsurface	50	NO_3^-	6.6	0.02	100	0.13	Martin et al. (1999)
Herbaceous/forest	surface	7.5	Total N	68	49	28	–	Schmitt et al. (1999)
Herbaceous/forest	surface	15	Total N	68	40	41	–	Schmitt et al. (1999)
Herbaceous/forest	surface	16.3	NO_3^-	–	–	78	–	Lee et al. (2003)
Herbaceous/forest	subsurface	8	NO_3^-	–	–	69	–	Dukes et al. (2002)†
Herbaceous/forest	subsurface	15	NO_3^-	–	–	84	–	Dukes et al. (2002)†
Herbaceous/forest	subsurface	6	NO_3^-	6.17	0.56	91	0.94	Borin and Bigon (2002)
Herbaceous/forest	subsurface	70	NO_3^-	11.98	1.09	91	0.16	Hubbard and Lowrance (1997)
Herbaceous/forest	subsurface	66	NO_3^-	5.8	0.17	97	0.09	Vidon and Hill (2004)
Herbaceous/forest	subsurface	33	NO_3^-	5.7	0.11	98	0.17	Vidon and Hill (2004)
Herbaceous/forest	subsurface	45	NO_3^-	17.8	0.18	99	0.39	Vidon and Hill (2004)
Herbaceous/forest	subsurface	70	NO_3^-	1.65	0.02	99	0.02	Martin et al. (1999)
Forest	surface	30	NO_3^-	0.37	0.08	78	0.01	Lynch et al. (1985)
Forest	surface	70	NO_3^-	4.45	0.94	79	0.05	Peterjohn and Correll (1984)
Forest	subsurface	50	NO_3^-	26	11	58	0.30	Hefting et al. (2003)
Forest	subsurface	200	NO_3^-	11	4	64	0.04	Spruill (2004)
Forest	subsurface	10	NO_3^-	6.29	1.15	82	0.51	Schoonover and Williard (2003)
Forest	subsurface	14	NO_3^-	0.02	0.02	0	0.00	Sabater et al. (2003)
Forest	subsurface	30	NO_3^-	0.02	0.01	50	<0.01	Sabater et al. (2003)
Forest	subsurface	50	NO_3^-	0.49	0.76	−55	−0.01	Sabater et al. (2003)
Forest	subsurface	15	NO_3^-	28.64	35.84	−25	−0.48	Sabater et al. (2003)
Forest	subsurface	20	NO_3^-	1.14	0.70	39	0.02	Sabater et al. (2003)
Forest	subsurface	20	NO_3^-	0.12	0.43	−258	−0.02	Sabater et al. (2003)
Forest	subsurface	15	NO_3^-	3.23	0.72	78	0.17	Sabater et al. (2003)
Forest	subsurface	20	NO_3^-	6.40	1.44	78	0.25	Sabater et al. (2003)
Forest	subsurface	55	NO_3^-	–	–	83	–	Lowrance et al. (1984)
Forest	subsurface	20	NO_3^-	–	–	83	–	Schultz et al. (1995)
Forest	subsurface	85	NO_3^-	7.08	0.43	94	0.08	Peterjohn and Correll (1984)
Forest	subsurface	204	NO_3^-	29.4	1.76	94	0.14	Vidon and Hill (2004)
Forest	subsurface	50	NO_3^-	13.52	0.81	94	0.25	Lowrance (1992)
Forest	subsurface	60	NO_3^-	8	0.4	95	0.13	Jordan et al. (1993)
Forest	subsurface	16	NO_3^-	16.5	0.75	95	0.98	Osborne and Kovacic (1993)
Forest	subsurface	16	NO_3^-	6.6	0.3	95	0.39	Haycock and Pinay (1993)
Forest	subsurface	15	NO_3^-	–	–	96	–	Hubbard and Sheridan (1989)
Forest	subsurface	165	NO_3^-	30.8	1	97	0.18	Hill et al. (2000)
Forest	subsurface	50	NO_3^-	6.26	0.15	98	0.12	Hefting and de Klein (1998)
Forest	subsurface	220	NO_3^-	10.8	0.22	98	0.05	Vidon and Hill (2004)
Forest	subsurface	50	NO_3^-	7.45	0.1	99	0.15	Jacobs and Gilliam (1985)
Forest	subsurface	10	NO_3^-	13	0.1	99	1.29	Cey et al. (1999)
Forest	subsurface	100	NO_3^-	5.6	0.02	100	0.06	Spruill (2004)
Forest	subsurface	30	NO_3^-	1.32	nd	100	0.04	Pinay and Decamps (1988)
Forest	subsurface	100	NO_3^-	12	nd	100	0.12	Spruill (2004)

Continued on next page.

Appendix 1. Continued.

Vegetation type	Flow path	Buffer width	N form	NO_3^- Concentration Mean influent	NO_3^- Concentration Mean effluent	Nitrogen removal effectiveness	NO_3^- removed	Study
		m		mg L^{-1}	mg L^{-1}	%	mg L^{-1} m^{-1}	
Forest	subsurface	60	NO_3^-	–	–	27	–	Groffman et al. (1996)
Forest	subsurface	30	NO_3^-	–	–	68	–	Spruill (2000)‡
Forested wetland	subsurface	31	NO_3^-	62.7	25.9	59	1.19	Hanson et al. (1994)
Forested wetland	subsurface	38	NO_3^-	30.6	6.7	78	0.63	Vellidis et al. (2003)
Forested wetland	subsurface	14.6	NO_3^-	–	–	84	–	Simmons et al. (1992)
Forested wetland	subsurface	5.8	NO_3^-	–	–	87	–	Simmons et al. (1992)
Forested wetland	subsurface	5.8	NO_3^-	–	–	90	–	Simmons et al. (1992)
Forested wetland	subsurface	6.6	NO_3^-	–	–	97	–	Simmons et al. (1992)
Forested wetland	subsurface	30	NO_3^-	1.06	nd	100	0.04	Pinay et al. (1993)
Wetland	surface	20	NO_3^-	57	50	12	0.35	Brüsch and Nilsson (1993)
Wetland	surface	20	NO_3^-	57	15	74	2.10	Brüsch and Nilsson (1993)
Wetland	subsurface	5	NO_3^-	6.56	1.55	76	1.00	Clausen et al. (2000)
Wetland	subsurface	5	NO_3^-	3	1.44	52	0.31	Clausen et al. (2000)
Wetland	subsurface	1	NO_3^-	1	–	96	–	Burns and Nguyen (2002)
Wetland	subsurface	200	NO_3^-	10.5	0.5	95	0.05	Fustec et al. (1991)
Wetland	subsurface	40	NO_3^-	77.48	0.31	100	1.93	Puckett et al. (2002)

† Values represent the average of 16 buffers.
‡ Values represent the average of 14 buffers.

Reproduced from Journal of Environmental Quality. Published by ASA, CSSA, and SSSA. All copyrights reserved.